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WIND RESOURCES PART I, THE EUROPEAN WIND CLIMATOLOGY

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1 Summary

The European Wind Atlas was produced with the purpose of establishing the meteorological basis for the assessment of the wind resources in the European Community. The comprehensive guidelines and computational tools which were generated together with the Atlas have constituted the basis for a number of similar studies outside the Community thereby making the calculated power production from wind turbines comparable from one country to another. A standardization seriously desired and needed by the wind energy community.

The Atlas depicts through maps and tables the regional distribution of the wind resources over land and a recent study has complemented this by presenting an offshore wind resource map. It appears from the Atlas that areas potentially suitable for wind energy applications are dispersed throughout all the countries of the European Community. It is the general experience that the Atlas provides a reliable picture of the overall and general distribution of the wind resources in most of the European Community. In regions with complicated topography and for which only sparse statistics exist the estimation of wind resources is very uncertain. To improve the situation in some of these regions the Commission has initiated measurements under the Joule 1 program in Northern Portugal, Spain, Italy, Greece and Ireland. Most of the measurements started in the Summer of 1991 and will run for two years. The overall impression of the intermediate results is they will not change the picture given in the Atlas much. However, they will add significantly to our understanding of the local distribution of the wind resources in mountainous terrain and thereby help to improve the model for flow over hills.

Recently a very comprehensive study has been undertaken by Deutsche Wetterdienst - Seewetteramt, Hamburg: "Wind and wave conditions in 55 European coastal sea areas, determined from weather and wave observations of voluntary commercial ships". The statistics presented in the study can be compared directly with the statistics in the Atlas maps. The comparison comes out very good, from the Northern Seas to the Aegean Sea there are very few discrepancies.

A careful comparison between the Wind Atlas predictions and the ship statistics can be used to rank a number of near-coastal stations in the Wind Atlas. It remains to be mentioned that the interpretation of the ship statistics is not without problems - on the contrary - but that will be discussed elsewhere.

2 The wind resources of the European Community

The wind resources over land. The map on Fig.1 from the Atlas depicts the regional distribution of the wind resources over land. It appears from the map that areas potentially suitable for wind energy applications are dispersed throughout all the countries of the European Community. It is the general experience that the Atlas provides a reliable picture of the overall and general distribution of the wind resources in most of the European Community. In regions with complicated topography and for which only sparse statistics exist the estimation of wind resources is very uncertain. To improve the situation in some of these regions the Commission has initiated measurements under the Joule 1 program in Northern Portugal, Spain, Italy, Greece and Ireland. Most of the measurements started in the Summer of 1991 and will run for two years. The overall impression of the intermediate results is they will not change the picture given in Fig.1 much. However, they will add significantly to our understanding of the local distribution of the wind resources in mountainous terrain and thereby help to improve the model for flow over hills. The Commission has further taken the initiative to supplement this model by one or more mesoscale models. The difference is that the present model is a very local model which can handle very detailed information of the topography out to approximately ten kilometers from the sites. In contrast the mesoscale models calculates the wind resource over several hundreds of kilometers in squares of one to five square kilometers. The models are currently being developed and they will be tested by a massive measurement programme where more than 30 instrumented mast of 30 meters height are currently being put into operation on Crete, Central Italy and Northern Portugal.

The wind resources offshore. An offshore position is in this context understood to be ten kilometers or more away from the nearest coast out to sea. The 15 colored wind resource maps in the Atlas are only colored over land such as the map on Fig.1. But this is only for reason of clarity, the statistics in the Atlas combined with some common knowledge of the European wind climate allows one straight away to construct an offshore wind resources map as shown in Fig.2. First of all, the basis idea behind the methodology of the Atlas is to present for each of the 220 stations used, regional representative wind statistics. By regional representative is meant that the derived statistics can be used out to a distance of approximately 100 km from the station. The experience tells that this hypothesis works well in non-mountainous terrain. The derived regional statistics is for each station presented for four terrain conditions - also called roughness classes - and one of them is open sea. And because more than 100 of the Atlas stations are either very close to the coast or even at sea it is straight forward to use the Atlas for estimating offshore wind resources. In addition, each of the maps, like Fig.1, contains a column giving the conditions at open sea. In the next section the resources portrayed by the map will be verified against the statistics in the Atlas and results from some recent studies.

The wind resources in the coastal region. When the air moves from sea to land areas or vice versa, two effects are of major importance for wind resource climatologies, namely: the change of surface roughness and thermal surface properties. Well away from the coast, the wind climate is either of the maritime or inland type, but in between it is a mixture. The width of the coastal zone varies with climate and topography. The Wind Atlas assumes a width of 10 km on either side of the coast.

Figures 3 and 4 from Ref.1 show the change of mean energy density at a height of 50 meters calculated for two different coastal zones. The change is given as function of distance from the coast. A North Sea coast in the Netherlands and a Mediterranean coast in France are taken as examples. Generally, the shape of the curves depends on the geographical position and orientation of the coast as well as the roughness class and orography of the coastal terrain. The conditions of a specific coast must in general be calculated by an appropriate siting procedure (Ref.2).

In the first example from a North Sea coast in the Netherlands it is seen that the change to open-sea conditions takes place over approximately 10 km whereas the change to land conditions occurs more abruptly, that is over approximately 4 km. The second example shows the conditions at the French Mediterranean coastline in a region strongly influenced by the Mistral. The two coastlines are perpendicular and parallel to the Mistral, respectively.

3 Verification of the offshore and coastal wind resource estimates

The roughness of a particular surface area is determined by the size and distribution of the roughness elements it contains; for land surfaces these are typically vegetation, built-up areas and the soil surface. The roughness length of surfaces covered by vegetation may vary with the wind speed. For example, the bending of stalks by the wind can change the form of the surface. A similar phenomenon occurs for water waves where both the height and the form of the waves are dependent on wind speed. From dimensional arguments, the well known Charnock's relation (see Ref.1) can be found. The relation gives the surface roughness as a function of the surface stress and the gravitational acceleration.

In the Atlas it was attempted to use both Charnock's relation and a fixed value for the roughness of water areas. It turned out that a fixed value of 0.0002 m gave results as good as the relation for the moderate to high wind speeds of interest to the Wind Atlas, hence all statistics in the Wind Atlas are obtained with this value. It should be noted that over some water areas the roughness can vary strongly with the time of the day and from season to season under the influence of phenomena as tidal waters and ice cover.

The coastal zone. It is the general belief that the roughness over water in the coastal zone is higher than at the open sea. The reason should be that the wave field is never in equilibrium with the wind field and therefore extracts more energy from the wind. In the Atlas, however the same roughness is used for all water surfaces the justification being the verification against measured wind statistics. Of special importance was the validation against high meteorological masts placed very close to the sea. For each mast the data from the lowest measurement level have been used to predict wind distributions at the higher levels. Tables 1 to 3 list Weibull parameters and wind power density for measured and predicted wind distributions for the Portuguese Ferrel mast, the Swedish Nasudden mast and the Danish Sprogø mast. It is obvious that the models ability to explain the variation of the wind statistics with height is quite good. Hence the use of a roughness length of 0.0002 m is not contradicted. The mast data also provides a test of the skill of the model to handel the modifications of the wind profile due to the different stability conditions over land and sea.

The major part of the verification in the Atlas is performed by letting the surface stations predicting each others wind statistics. And because half of the stations are located in the coastal zone, the success of the model validation heavily depends of is ability to model local variations in this zone. The conclusion that can be drawn from the validations in the Atlas is that under reasonable moderate conditions the model performs very well. When the conditions are complex such as in some Mediterranean areas with strong thermal differences in the horizontal combined with steep reliefs then the model results might prove less reliable.

The open sea. The Wind Atlas for the North Sea and the Norwegian Sea (Ref.3) provides an overall picture of the wind conditions in the Northern waters of Europe. A picture which is in good accordance with that given by Figures 1 and 2. This can be seen from Fig.5 extracted from Ref.3: The average wind field in about 1000 m above sea level. The lines drawn are based on computed averages over a 27 years period from 1957 to 1981 for grid points with a spacing of 150 km. Four wind values per day are obtained from analyzing more than 39000 weather maps.

It is quite obvious that very few data sets exists from fixed installations at open sea. Those which can be found are often measured at production platforms, they are difficult to access, they are usually infested with large gaps of missing data and the influence of the platform on the wind flow to the anemometers are considerable and difficult to correct for. Nevertheless that's what is available and Ref.6 presents an analysis of eight years of data (1982-1989) from the platform K13 situated 100 km from the Dutch coast. At a height of 75 m a mean value of 9.0 m/s is found which compares well with Fig.2. The corresponding Weibull parameters are A = 10.25 m/s and k = 2.04; it is found that the Weibull distribution gives a good fit to the data. The average roughness length is found to be close to 0.0002 m/s.

Ref.7 gives a mean wind speed of 9.5 m/s measured over almost 4 years at 50 meters height at a gas platform located 50 km South of Roches Point (Irish Coast). Again, this value compares well with Fig.2.

A very comprehensive study has been undertaken by Deutsche Wetterdienst - Seewetteramt, Hamburg: "Wind and wave conditions in 55 european coastal sea areas, determined from weather and wave observations of voluntary commercials ships" (Ref.6). A large number of ships carry out meteorological and oceanographic observations along the route of the ships at fixed 3-hourly time intervals. The observations start as soon as a ship is out of the harbour; the determination of the wind speed is done by an estimation of the wind force according to the appearance of the sea surface and following the well known Beaufort scale. Numerous studies have been performed over the years in order to establish the correct conversion from the Beaufort scale to meters per second. In short, for the purpose of this paper it can be noted that a generally accepted scale exists and that the resulting wind speeds in m/s are considered representative for the winds 25 meters over the sea surface. Hence the statistics presented in Seewetteramt study can be compared directly with Fig.2. The comparison comes out very good, from the Northern seas to the Aegean Sea there are very few discrepancies. When offshore predictions from single station from the Wind Atlas are compared with statistics from the ships large discrepancies are found, especially for Portugal and Spain. But also very good agreements are found, for example where the Mistral meets over the Mediterranean Sea the Atlas station Istres predicts an energy density of 828 Wm-2 and the ships statistics 822 wm-2. Other examples of good agreement are Roches Point, Ireland (658 653), Rønne, Denmark (527 518), Middelkerke, Belgium (566 599), Brest, France (616 656), Faro, Portugal (334 387), Barcelona, Spain (243 282).

A careful comparison between the Wind Atlas predictions and the ship statistics could well lead to a subset of stations to be recommended and therefore it is the intention to do so. It remains to be mentioned that the interpretation of the ship statistics is not without problems - on the contrary - but that will be discussed elsewhere.

4 Conclusion

The European Wind Atlas was published in 1989, but work has been carried out since then for improving the knowledge og the European wind climatology. Comprehensive measurements have been initiated in several EC countries in mountainous terrain with a twofold purpose: to help the understanding and the modelling skill of the local distribution of the wind resources in such terrain and to gain general climatological knowledge. Preliminary analysis of some of the measurements leaves the impression that the overall distribution as given by Fig.1 will not be changed very much.

The distribution of the European wind resources over open water seems to be known to a sufficient degree of accuracy. It is however a question whether the open sea resources will ever be utilized. The coastal zone on the contrary attracts much more attention, but in these areas it is of much importance for accurate resource estimation that reliable wind statistics are utilized and that the siting procedure is capable off handling the influence on the wind profile of the land-water transitions and the topography of the coastal area.

5. References

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[2] Troen, I. and E.L. Petersen, 1989: *European Wind Atlas*. Published for the Commission of the European Communities by Risø National Laboratory. 656pp.

[3] Børresen, J.A., 1987: *Wind Atlas for the North Sea and the Norwegian Sea*. Norwegian University Press, The Norwegian Meteorological Institute. 183pp.

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[5] Burke, L., 1988: *EC Wind Energy Atlas: An Assessment of the Irish Results*. Work group document. 14pp.

[6] Schmidt, H., J. Püttker, 1991. *Wind and wave conditions in 55 European coastal areas, determined from weather and wave observations of voluntary commercial ships*. Report from Deutscher Wetterdienst to Germanischer Lloyd. 30pp.

Table 1: Ferrel mast, Portugal. The data cover the two years 1977-78. Located at the coast 10 km northeast of Cabo Carvoeiro. The mast was situated 3.5 km northeast of the village of Ferrel. The distance to the sea is 300 m to the northwest. To the southeast the landscape is undulating and covered by vegetation. Close to the mast the terrain consists of sand dunes.

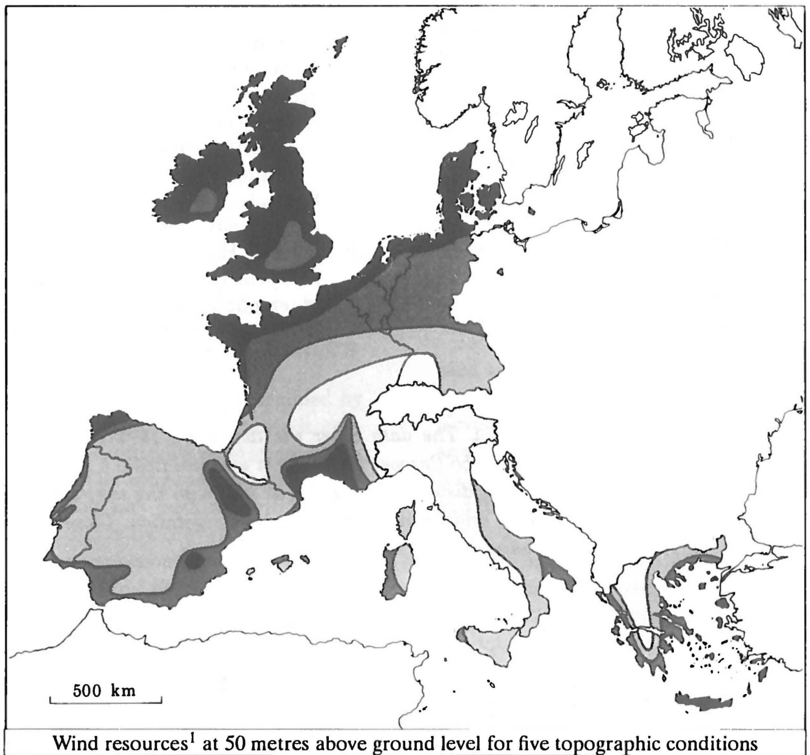
Height	Measured			Predicted		
z	A	k	E	A	k	E
10 m	5.8	1.83	171	5.8	1.83	171
30 m	7.2	2.09	289	7.0	1.94	286
100 m	8.6	2.33	450	8.4	2.04	467

Table 2: Näsudden mast, Sweden. Data cover the years 1980-85. The mast is located on the small peninsula Näsudden on the island of Gotland. The distance to the Baltic sea is a little more than one kilometre in directions from south to southwest. Near the mast the terrain consists of low dense bushes and scattered trees. Further away from the mast the terrain is hilly and forested.

Height	Measured				Predicted			
z	M	A	k	E	M	A	k	E
10 m	5.1	5.8	1.99	157	5.1	5.7	1.96	154
38 m	7.0	7.8	2.02	381	7.0	7.9	2.10	385
54 m	7.5	8.4	2.10	465	7.7	8.6	2.13	493
75 m	8.0	9.0	2.10	555	8.1	9.1	2.13	585
96 m	8.4	9.5	2.12	647	8.4	9.5	2.12	654
120 m	8.6	9.7	2.13	692	8.8	9.9	2.10	750
145 m	9.1	10.3	2.15	818	9.1	10.3	2.08	845

Table 3: Sprogø mast, Denmark. Data cover 4 years (1983-88). The mast is situated on the small island of Sprogø in the middle of Storebælt (Great Belt). The mast stands on a long narrow spit of land only 50 m wide and extending 300 m east of the island proper. Except for the 240°-270° sector, the approach to the mast is over several kilometres of open water. The distance to the islands of Sjælland to the east and Fyn to the west is aproximately 10 km.

Height	Measured			Predicted		
z	A	k	E	A	k	E
8 m	7.1	2.02	289	7.0	2.01	282
18 m	7.6	2.07	342	7.8	2.14	357
55 m	8.9	2.26	513	8.9	2.33	499
68 m	9.2	2.31	547	9.2	2.31	555

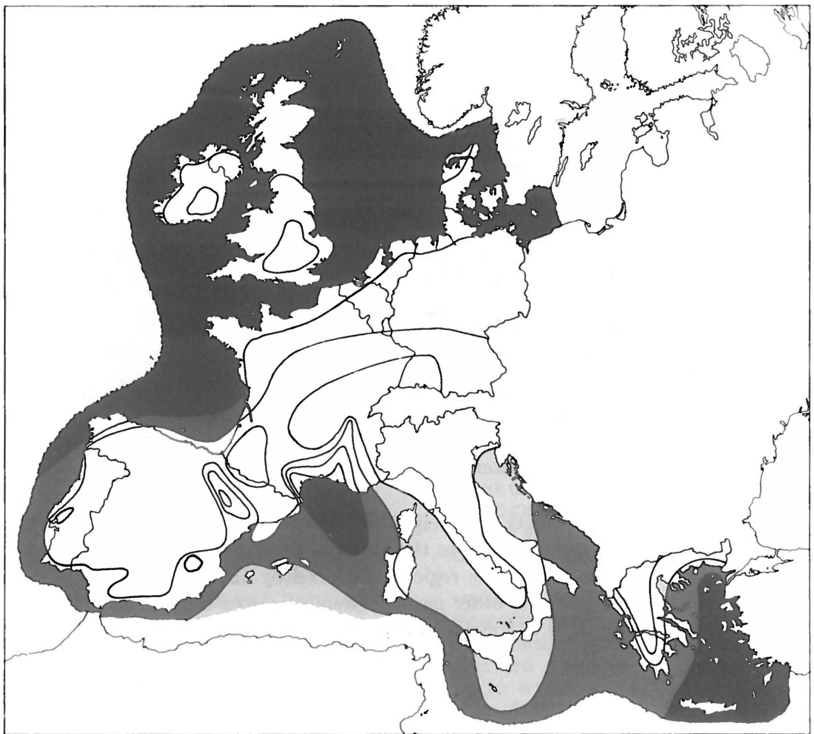


Wind resources[1] at 50 metres above ground level for five topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

1. The resources refer to the power present in the wind. A wind turbine can utilize between 20 and 30% of the available resource. The resources are calculated for an air density of 1.23 kg m^{-3}, corresponding to standard sea level pressure and a temperature of 15°C. Air density decreases with height but up to 1000 m a.s.l. the resulting reduction of the power densities is less than 10%, see Table B.1 in Appendix B.
2. Urban districts, forest and farm land with many windbreaks (roughness class 3).
3. Open landscapes with few windbreaks (roughness class 1). In general, the most favourable inland sites on level land are found here.
4. The classes pertain to a straight coastline, a uniform wind rose and a land surface with few windbreaks (roughness class 1). Resources will be higher, and closer to open sea values, if winds from the sea occur more frequently, i.e. the wind rose is not uniform and/or the land protrudes into the sea. Conversely, resources will generally be smaller, and closer to land values, if winds from land occur more frequently.
5. More than 10 km offshore (roughness class 0).
6. The classes correspond to 50% overspeeding and were calculated for a site on the summit of a single axisymmetric hill with a height of 400 metres and a base diameter of 4 km. The overspeeding depends on the height, length and specific setting of the hill.

Figure 1: Distribution of wind resources in Europe. By means of the legend the available wind energy at a height of 50 meters can be estimated for five topographicconditions, (from Ref. 1).



Wind resources over open sea (more than 10 km offshore) for five standard heights

	10 m		25 m		50 m		100 m		200 m	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5-8.5	450-650	8.0-9.5	600-900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0-7.5	250-450	6.5-8.0	300-600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Figure 2: Distribution of wind resources in Europe over open sea. The table is calculated by means of figures 4.2 and 4.3 in Ref. 1.

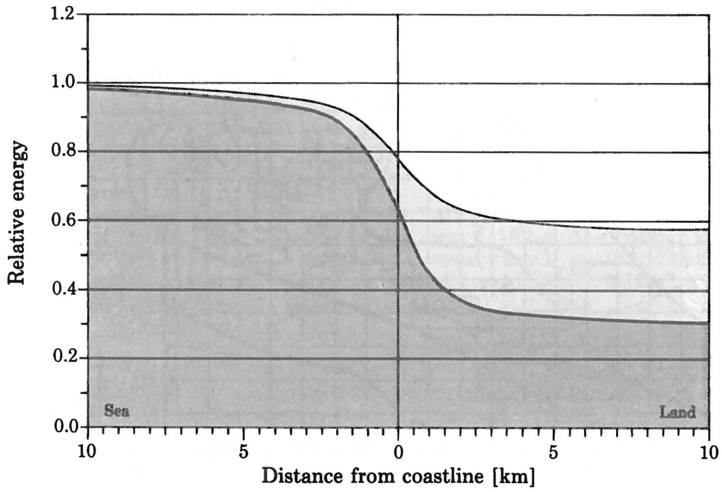


Figure 3: Mean energy density at a height of 50 m calculated as a function of the distance to the North Sea coast in the Netherlands for two different land roughnesses. The coast is oriented SW-NE and the terrain is of roughness class 1 (upper line) and roughness class 3 (lower line), respectively, (from Ref. 1.).

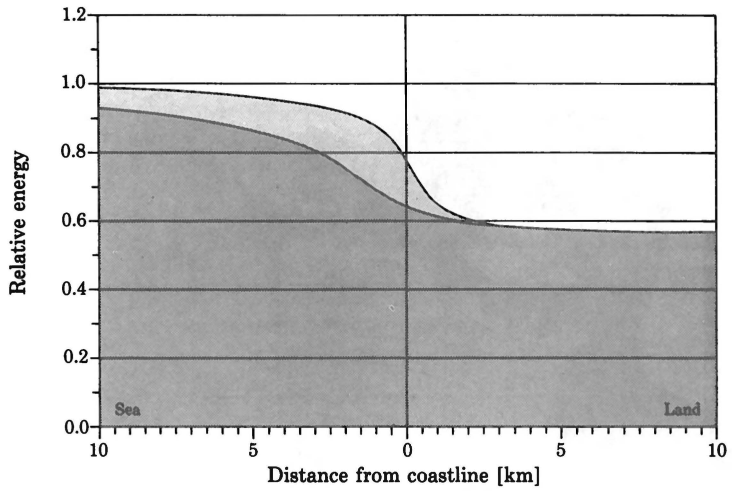


Figure 4: Mean energy density at a height of 50 m calculated for two coastlines as a function of the distances to the Mediterranean Sea in France. the two costalines are situated in the region influenced by the Mistral; one is perpendicular (lower line) the other parallel (upper line) to the direction of the Mistral. The terrain is of roughness class 1, (from Ref 1.)

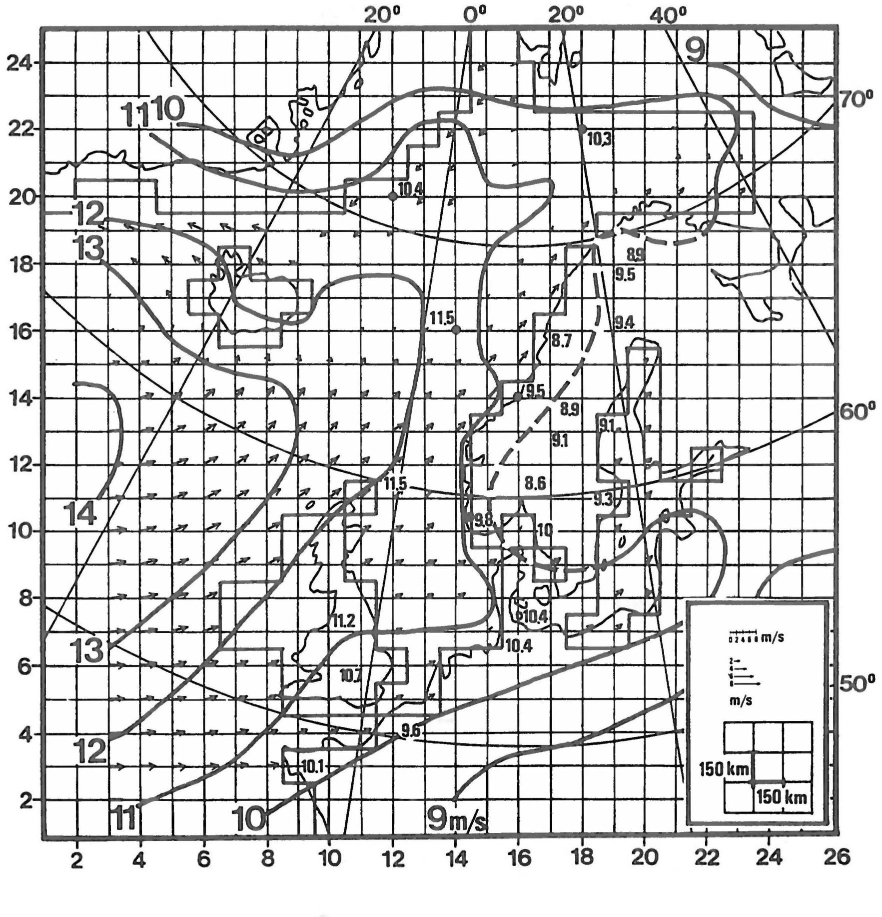


Figure 5: The average wind field in about 1000 m above sea level. The lines drawn are based on computed averages over a 27 year period from 1957 to 1981 for all grid points. Four wind values are available per day. The inserted figures are averages from measurements at the 850 mb level made by radiosondes (Ref. 3).